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Determination of Spectrally Resolved Transmittance and Extinction Coefficients for Obscurants at Smoke Week XIV

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13. ABSTRACT *(Maximum 200 words)*

Since the completion of Smoke Week XIII in May 1991, significant enhancements have been incorporated into the U.S. Army Research Laboratory, Battlefield Environment Directorate's Mobile Atmospheric Spectrometer (MAS). The key components of the MAS are a Fourier transform spectrometer and a 31-in Coudé telescope. The useful spectral coverage of the instrument is about 800 to 5000 cm^{-1} (2 to 12.5 μm). Although the instrument is capable of spectral resolution as high as 0.04 cm^{-1}, a resolution of 4 cm^{-1} was used during Smoke Week XIV. In preparation for Smoke Week XIV, a high-speed parallel spectrometer-to-computer interface was installed. Although this interface arrived too late to optimize fully, the increase in spectrometer performance was impressive. Rather than slewing on and off source, a mechanically chopped source was used to increase data acquisition rate and maintain a constant line of sight. With these two enhancements, the number of spectra collected increased by a factor of six. With more than 9,000 smoke spectra collected, a new data analysis approach was required. This requirement evolved into a three-dimensional spectral movie that displays transmittance (or radiance) versus spatial frequency as a function of time. In this manner, trials incorporating hundreds of spectra may be viewed. The MAS line of sight was in close proximity and parallel to the nephelometer grid. As a result, obscurant concentration length (CL) as determined from nephelometer data and transmittance as determined from MAS data have been manipulated to derive spectrally resolved mass extinction coefficients for selected obscurants.

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1. Background

Obscurant tests traditionally have placed heavy emphasis on the use of broadband transmissometers in the characterization of optical properties of test materials. The broadband transmissometry has many attractive features, including high temporal resolution, relatively simple instrumentation, and relatively small data storage requirements. Unfortunately, it is impossible to match a transmissometer response function to the multitude of electro-optical systems that must contend with optically obscured battlefield environments. The inherent broadband nature of many transmissometers, therefore, severely limits the usefulness of such data. Researchers using such data are at a risk of formulating erroneous results.

Transmittance measurements made with the Battlefield Environment Directorate's (BED) Mobile Atmospheric Spectrometer (MAS) overcome this shortcoming of the broadband instruments. [2] While the traditional transmissometer can obtain only one transmittance data point per spectral window per time interval, a Fourier transform spectrometer (FTS) can provide hundreds of transmittance data points per spectral window per time interval. High-resolution FTS obscurant transmittance spectra can be convolved with *any* infrared system response function desired and thereby remove the uncertainty that accompanies the comparison of transmissometers with differing response functions. The result can be a more accurate prediction of the system performance.

The primary goal of the MAS support of Smoke Week XIV was to demonstrate the utility of spectrally resolved measurements in the obscurant test setting. The transmittance and radiance spectra of the obscurants and munitions have been made available to the scientific community through the Atmospheric Aerosols and Optics Data Library (AAODL). Nephelometer and transmittance data have been manipulated to derive obscurant mass extinction coefficients for selected materials. Figure 1 depicts the MAS.

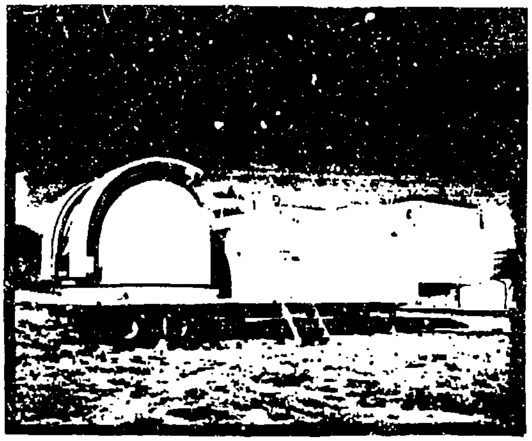

Figure 1. Mobile Atmospheric Spectrometer (MAS).

2. Enhancements in Data Acquisition

Significant enhancements were employed at Smoke Week XIV. [5] At Smoke Week XIII (1991) the spectrometer and host computer communicated via a serial interface. Before the system was shipped to Eglin Air Force Base for Smoke Week XIV (1992), a high-speed parallel interface was installed. Because of the lack of time to become familiar with this upgrade, the system was not optimized to its fullest extent; however, the increase in data acquisition rates was exceptional.

A second enhancement dealt with the method for obtaining source and path radiance spectra. During Smoke Week XIII the telescope had to repeatedly cycle from on-source to 0.5° off-source which changed the background and was an inefficient use of time. For Smoke Week XIV a source chopper was employed. Communications from the host computer to the chopper were accomplished via communications wire.

3. Methodology

The transmittance of a sample of material at radiation frequency ν is defined as the ratio of the radiant power at frequency ν exiting the material to the radiant power at that frequency incident upon the material

$$T(\nu) = \frac{I(\nu)}{I_o(\nu)}. \tag{1}$$

For an obscurant measurement, the transmittance through the path with the obscurant relative to the clear air path is required rather than the absolute transmittance of the entire path. The spreading factors and the instrument response function remain unchanged when comparing the path with the obscurant to the path without the obscurant; however, a simpler measurement methodology can be applied. Without path radiance and background effects, the relative transmittance of the obscurant is the point-by-point ratio of the obscurant spectrum to the clear air spectrum. Path radiance and background radiation may contaminate the raw signals and thus must be removed.

$$I_o(\nu) = S_{clear} - S_{bkg}$$

and

$$I(\nu) = S_{obs} - S_{path};$$

therefore,

$$T(\nu) = \frac{S_{obs} - S_{path}}{S_{clear} - S_{bkg}}. \tag{2}$$

All the quantities of S are functions of ν.

An effective measurement methodology is to measure the four quantities of S over as short an interval as practical. It is especially important for the obscurant and path radiance data to be close together in time because of the transient nature of the typical obscurant cloud. Clear air data

may be acquired before or after the obscurant is present; but, in general, pretrial clear air data are less likely to be contaminated by residual obscurant that may not be obvious to an observer. In repetitive, alternating sequence, obscurant spectra and path radiance spectra are collected. Path radiance spectra can be obtained by blocking the source or pointing the collecting telescope slightly off the source. Pointing the collecting telescope slightly of the source was used at Smoke Week XIII. To enhance the data acquisition rates, a source chopper was incorporated into the system for Smoke Week XIV.

4. Instrumentation

The key components of the MAS for support of the activities at Smoke Week XIV were the FTS and the 31-in Coudé telescope.

4.1 Fourier Transform Spectrometer Configuration

The MAS FTS consists of a scanning Michelson interferometer with associated optics and control electronics and a dedicated computer system. Depending on the detector, beamsplitter, and source in use, the spectrometer can cover a segment of the spectral region from about 700 to 20,000 cm^{-1} (0.5 to 14 μm).

The Fourier spectrometer was configured with a potassium bromide (KBr) substrate beamsplitter with a mercury-cadmium telluride (MCT) detector. The useful spectral coverage was about 800 to 5000 cm^{-1} (2 to 12.5 μm). Although the instrument is capable of spectral resolution as high as 0.04 cm^{-1}, a resolution of 4 cm^{-1} was used during Smoke Week XIV. Very high resolution is not needed or practical for most obscurant transmittance measurements because of time resolution considerations.

There are 234 data points in the 800- to 1250-cm^{-1} spectral region, 114 points in the 2020- to 2240-cm^{-1} spectral region, 316 points in the 2390- to 3000-cm^{-1} spectral region, and 492 points in the 4050- to 5000-cm^{-1} spectral region.

A factor in choosing the instrument configuration was that a KBr beamsplitter was clearly the best choice for most mid-infrared work, but KBr is hygroscopic. Great care must be exercised to avoid damage during humid weather and especially during periods of precipitation. Since a KBr beamsplitter was damaged beyond use during a period of high humidity during Smoke Week XIII, both a replacement Kbr beamsplitter and a moisture-insensitive (ZnSe) beamsplitter were in the MAS inventory for Smoke Week XIV. The KBr beamsplitter was used during all tests because the test site experienced good weather and the ZnSe beamsplitter was insensitive to radiation shorter than 3 μm.

When time permitted, between trials, the data acquisition sequence for each trial included high signal-to-noise ratio clear air source and clear air background data. For all clear air data, 100 instrument scans were coadded. Each interferogram required about 35 s to acquire, with another 2.3 s required for transfer and storage. For most trials, clear air data acquisition was initiated at about T - 3 min, and two complete cycles were performed. When time permitted, a similar post-test clear air acquisition sequence was carried out.

Obscurant and path radiance interferograms were obtained by coaddition of two scans. Coaddition of two scans required 0.7 s. Transfer and storage again required about 2.3 s per interferogram. Each interferogram, therefore, required 3 s to acquire and store. Each complete measurement cycle of obscurant and path radiance interferograms required 6 s.

Coaddition of multiple instrument scans serves two important functions: (1) it improves the signal-to-noise ratio of the interferograms and the resulting spectra (the signal-to-noise ratio increases proportionally with the square root of the number of instrument scans coadded), and (2) it reduces the signal variation that results from atmospheric turbulence.

The usual MAS sources are a quartz-halogen lamp and a temperature controlled blackbody that can reach 1000 °C. In either case, the radiation is collimated with a modified searchlight. The blackbody is the source of choice for most of the mid-infrared region, while the lamp provides better performance for wavelengths shorter than 2 μm. Therefore, the near-infrared and mid-infrared regions require different sources, and only one region can be optimized at a time.

4.2 *Coudé Telescope*

The MAS Coudé-mounted telescope is a classical Cassegrain telescope consisting of a 31-in diameter parabolic primary mirror and a 6-in diameter hyperbolic secondary mirror. Segments of the optical path are coaxial with the elevation and azimuth rotational axes of the telescope so the beam position on the optical bench is invariant with respect to the pointing.

The telescope uses a sophisticated servo loop control system. The angular resolution is 1.24 arc-s. A desktop computer provides the user interface. A control program has been written to translate simplified commands into valid telescope instructions. The telescope control program provides the capability to fine-tune the pointing to optimize the signal. Once the correct coordinates have been found, it is very easy to return to a given position with high precision.

5. Data Reduction

Programs written in Fortran were used to reduce all data, and MS-DOS-based computers acted as hosts. Batch-oriented data analysis programs were produced and fine-tuned before Smoke Week XIV.

Because data acquisition required only 0.7 s, a data file can be thought of as a snapshot of the changing spectrum at the time listed in the file header. The spectral intervals in which atmospheric opacity significantly impaired the ability to retrieve the obscurant transmittance are not included in the files, and breaks in the listings are used to delineate the resulting discontinuities in the spectral coverage.

6. Analysis Enhancements: Three-Dimensional Spectroscopic Movie

With more than 9,000 spectra collected, the next significant task was data analysis. In the past, the only means a researcher had to view data were commercial plot packages in which a few spectra could be displayed. A decision was made that with such a large volume of data a new approach was required. The requirement evolved into a three-dimensional (3-D) spectral movie that displays transmittance (or radiance) versus spatial frequency as a function of time. Complete trials incorporating hundreds of spectra may be viewed in a movie. The aspect angle may be changed during operation. A version of the program under development permits the movie to be paused at any time, reversed or zoomed.

7. Example Spectra

MAS spectra provide useful insight into the behavior of the obscurant materials. Frequency dependence of the smoke transmittance that cannot be observed with broadband transmissometers is readily apparent in the spectra.

In general, in the mid-infrared, some materials exhibit only a smooth falloff with increasing frequency. Others, however, exhibit a wealth of interesting detail. Among the materials investigated were red phosphorus (figures 2a, 2b), graphite (figure 3), kaolin (figure 4), brass (figure 5), aluminum (figure 6) and silica (3-D figure 7). Radiance spectra of munitions and a flare were taken at Smoke Week XIV. In the 3-D spectra of a flare (figure 8), note the red spike (2240 cm^{-1}) and blue spike (2390 cm^{-1}) due to heated atmospheric CO_2. The presence of two small emission features at 4275 and 4530 cm^{-1} is also of interest, though not understood at this time. Some fog oil spectra (figure 9) exhibit the well-known C—H stretch vibrational-rotational band at about 2800 cm^{-1}.

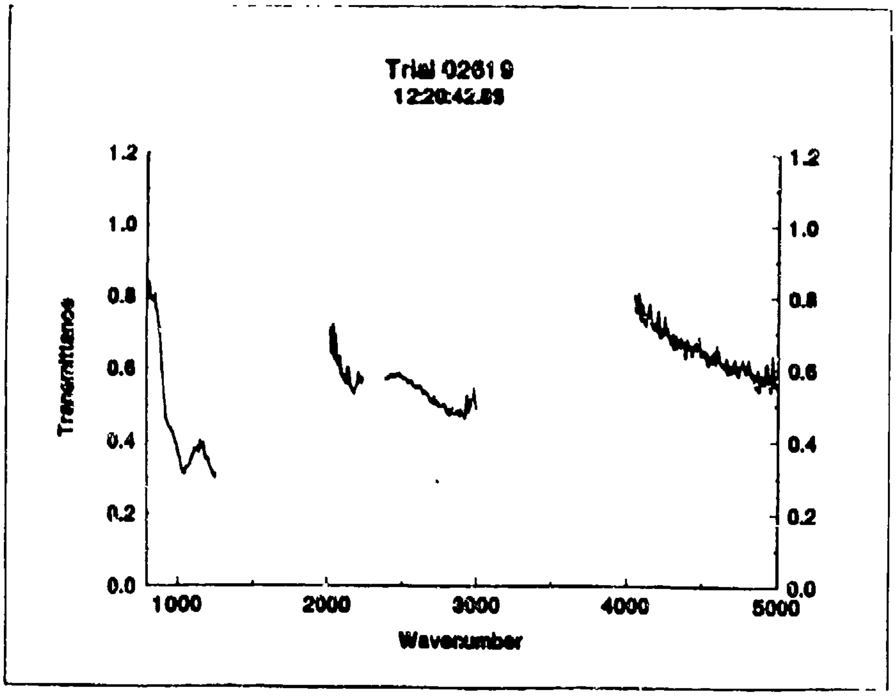

Figure 2a. Red phosphorus transmittance spectra.

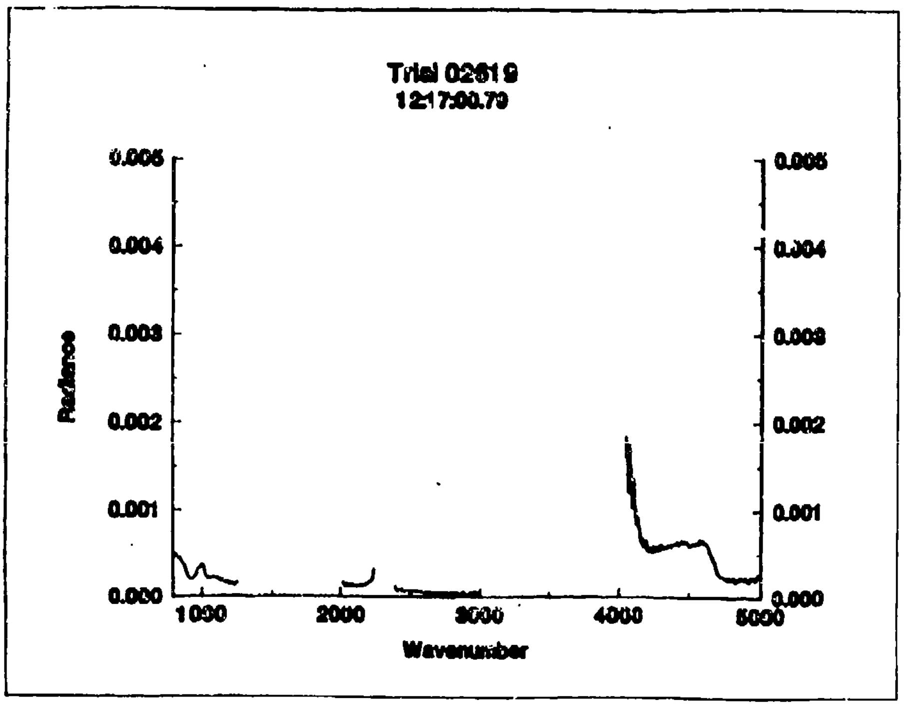

Figure 2b. Red phosphorus radiance spectra.

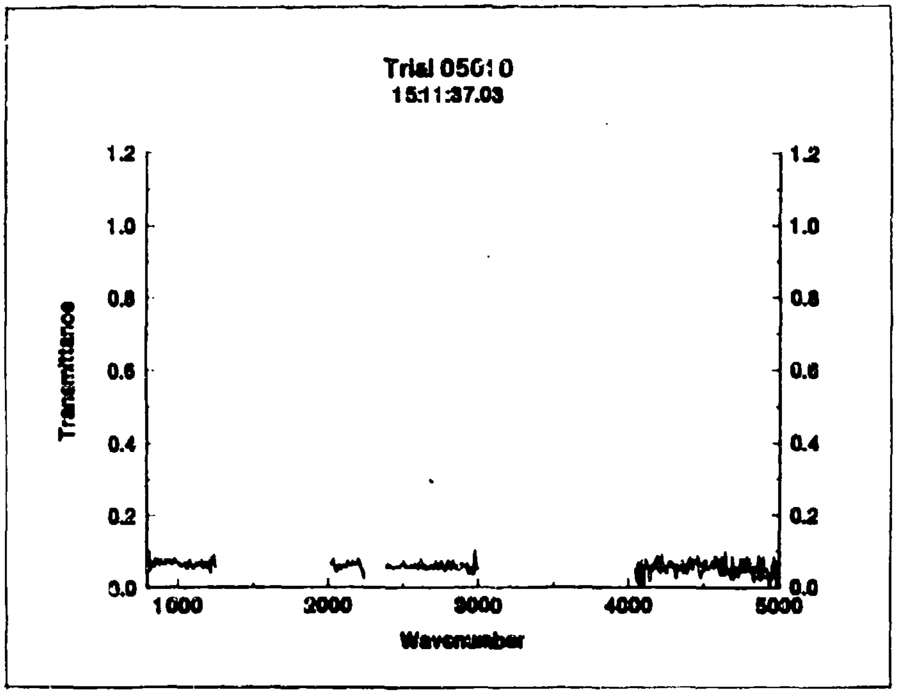

Figure 3. Graphite transmittance spectra.

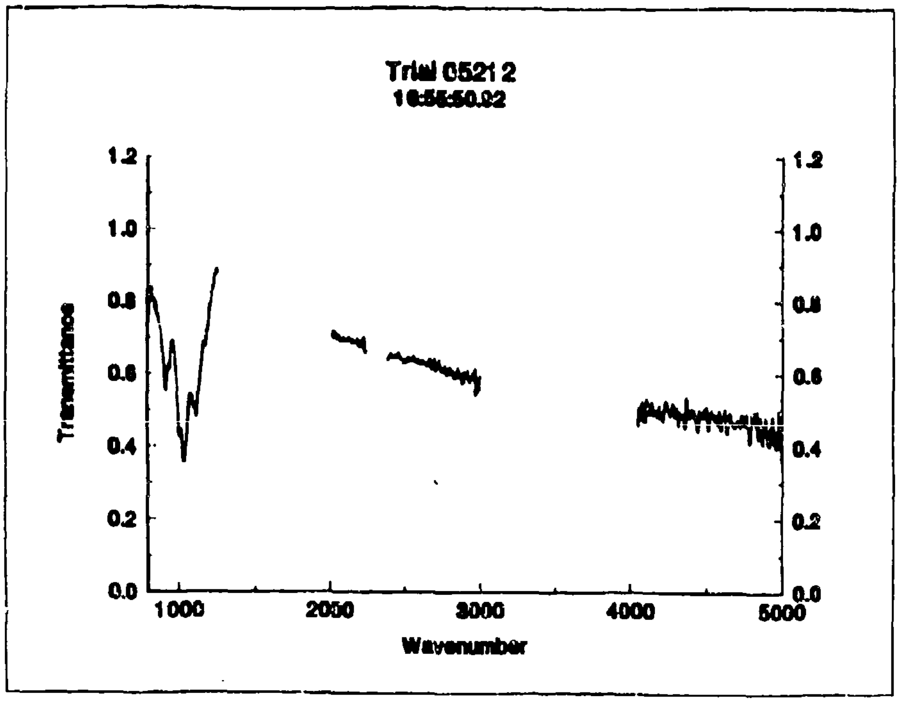

Figure 4. Kaolin transmittance spectra.

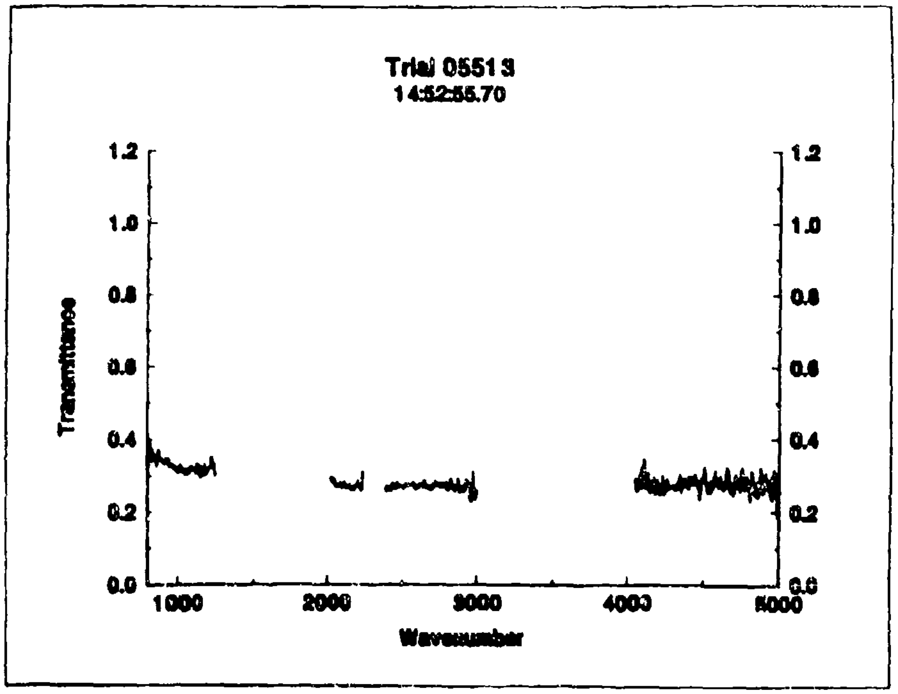

Figure 5. Brass transmittance spectra.

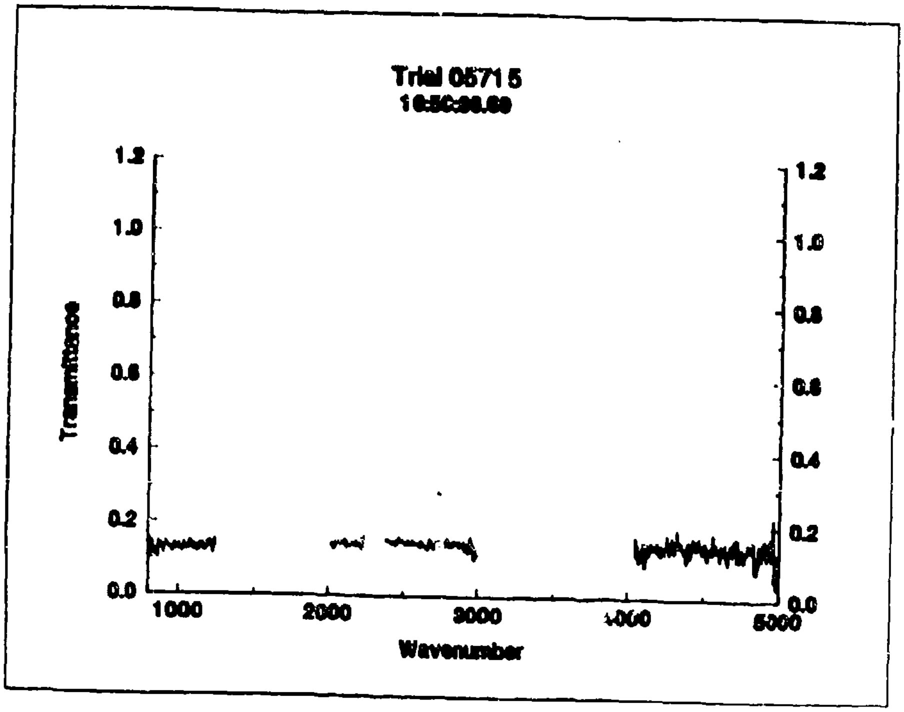

Figure 6. Aluminum transmittance spectra.

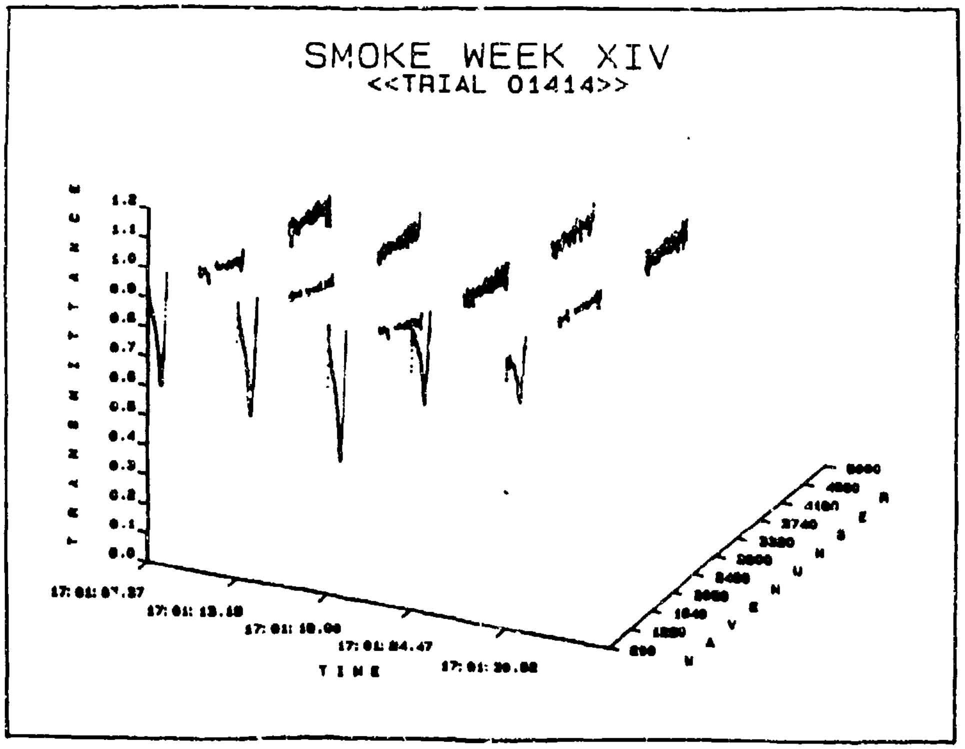

Figure 7. Silica spectra as a function of time.

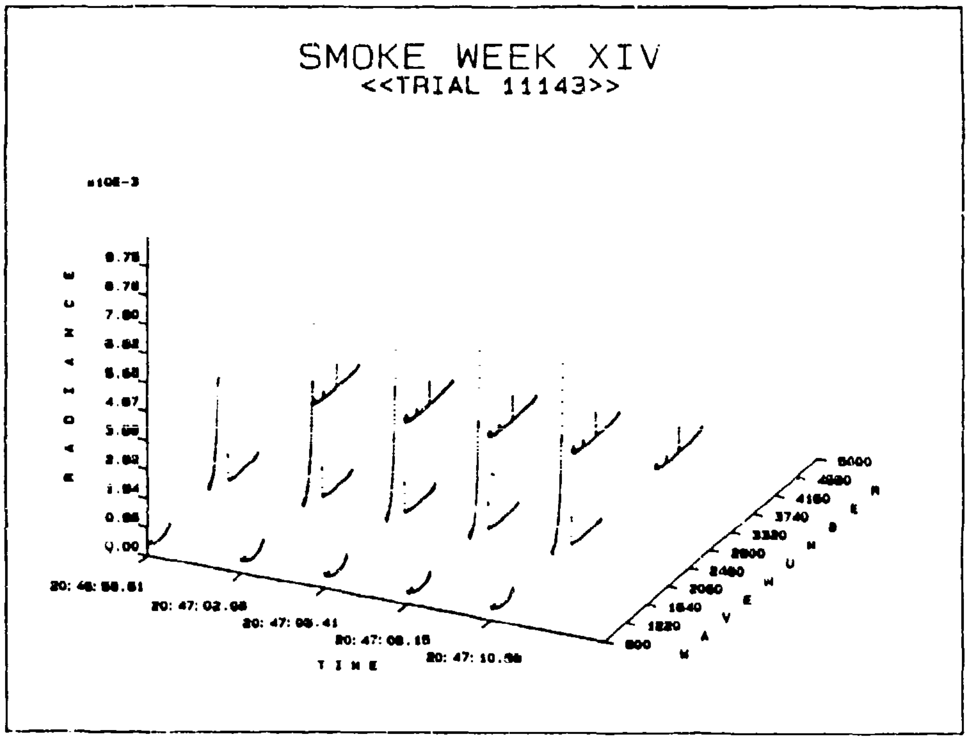

Figure 8. Radiance spectra of a flare.

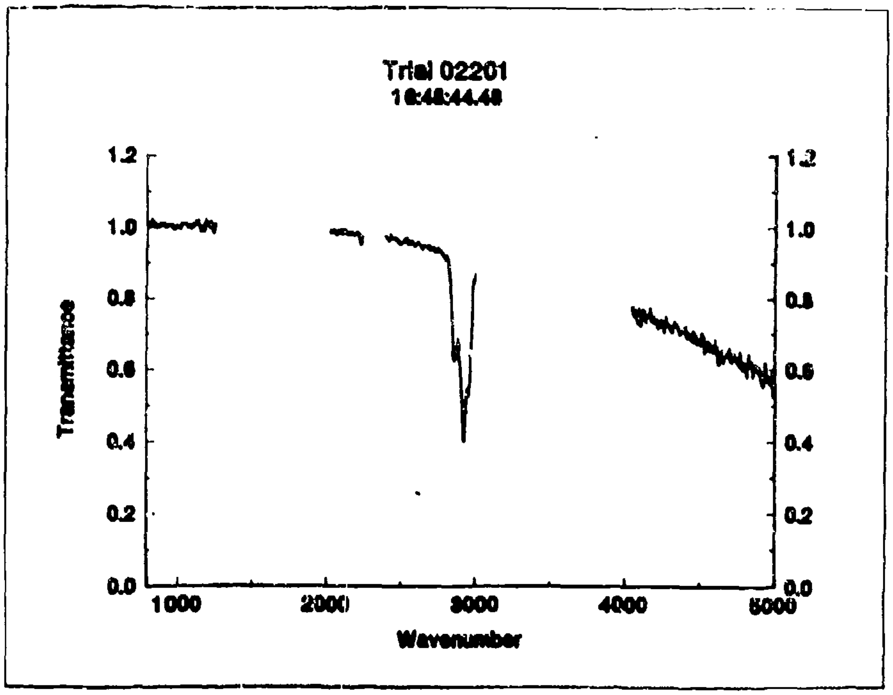

Figure 9. Transmittance spectra of fog oil.

8. Determination of Selected Spectrally Resolved Mass Extinction Coefficients

The MAS line of sight was in close proximity and parallel to the nephelometer grid. As a result, obscurant concentration length (CL) as determined from nephelometer data and transmittance as determined from MAS data have been manipulated to derive spectrally resolved mass extinction coefficients for selected obscurants. A word of caution -- few coefficient spectra have been analyzed. The preliminary results presented here may not be typical of all data. Mass extinction coefficients have been derived from measurements made at Smoke Week XIII (1991) using the ARL broadband Multipath Transmissometer/Radiometer (MPTR). [3] These results, along with coefficients maintained in the ARL Electro-Optical Systems Atmospheric Effects Library (EOSAEL) [4] are compared with MAS derived data. The MAS data show breaks where the atmosphere is opaque. As a result, the data tend to become noisy at the break points. Also, since the MAS detector response is peaked in the 8- to 12-μm (800 to 1250 cm^{-1}) region, the response is lower and the data are more noisy at shorter wavelengths (higher frequencies). MAS and MPTR data compare favorably for aluminum (figure 10). Results from MAS and EOSAEL data for graphite (figure 11) also appear promising. The MPTR 3- to 5-μm band average for brass (figure 12) differs from MAS data to some extent. Compounding the problem, some researchers (Bruce, 1993) report results as high as 1.8 m^2/g.*

The fog oil results (figure 13) demonstrate the utility of spectrally resolved measurements. While the EOSAEL band averaged data compare with the MAS data in the 8- to 2-μm region, the band average in the 3- to 5-μm region does not compare well with the spectrally resolved MAS data. Fog oil exhibits the well-known hydrocarbon stretch vibrational-rotational band at about 2800 cm^{-1}.

*C. W. Bruce, 1993, Private communication, U.S. Army Research Laboratory, Battlefield Environment Directorate, White Sands Missile Range, NM 88001-5501.

For a parallel arrangement, nephelometer-based mass concentrations and transmittance measurements are related according to Beer's law:

$$T(t) = e^{(-\alpha CL(t+\Delta t))} \tag{3}$$

where:

T = transmittance

t = time

Δt = time for cloud to move from spectrometer line of sight to nephelometer grid

α = Mass extinction coefficient in m^2/g

CL = Concentration Length in g/m^2

The concentration length is described as follows:

$$CL(t) = \int C(r,t)dr \tag{4}$$

where:

$C(r,t)$ = Obscurant mass concentration at distance r along the nephelometer grid at time t

dr = change in position

L = path length as determined by the nephelometers

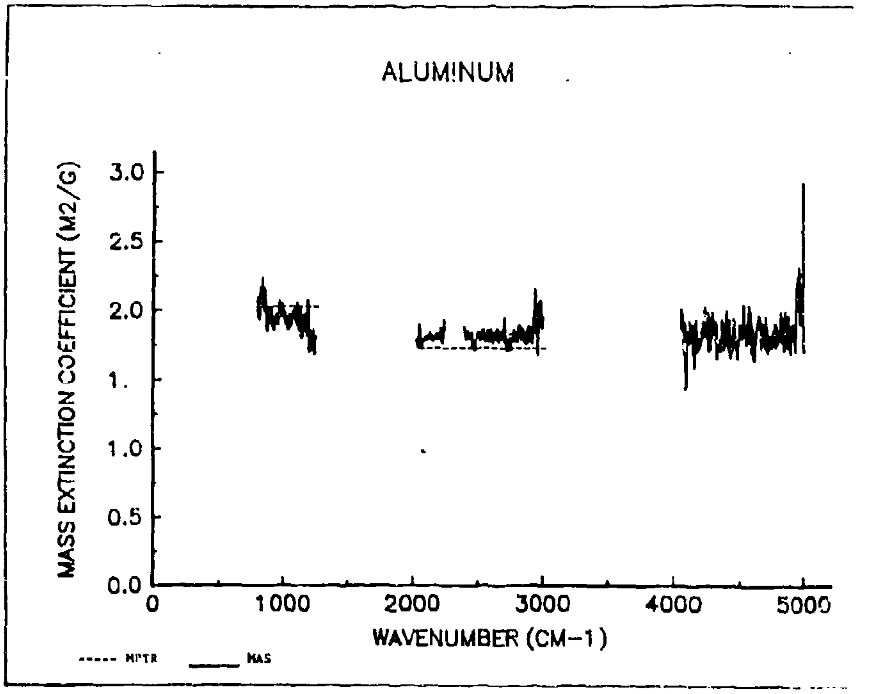

Figure 10. Spectrally resolved mass extinction coefficients for aluminum.

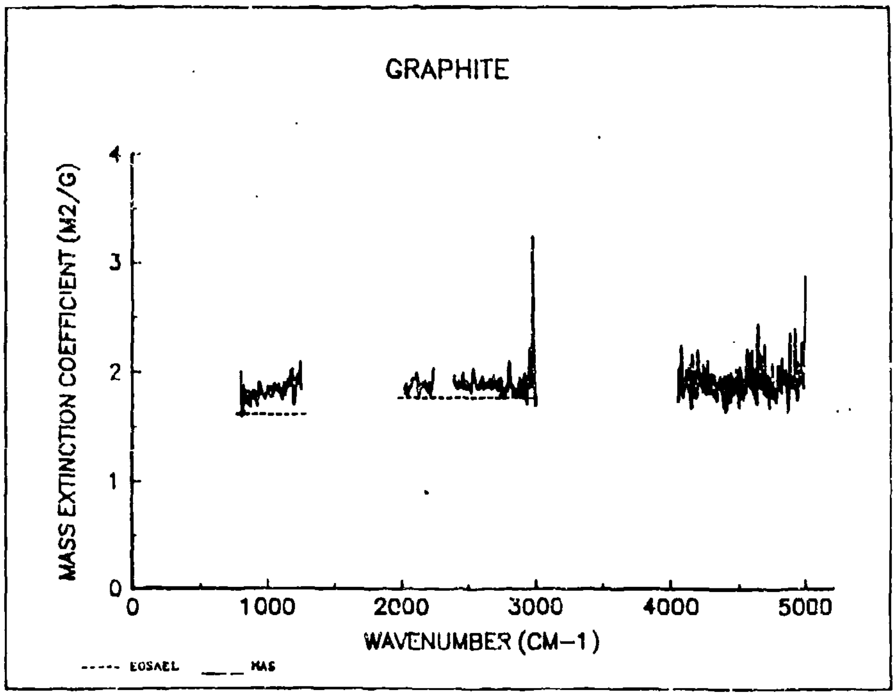

Figure 11. Spectrally resolved mass extinction coefficients for graphite.

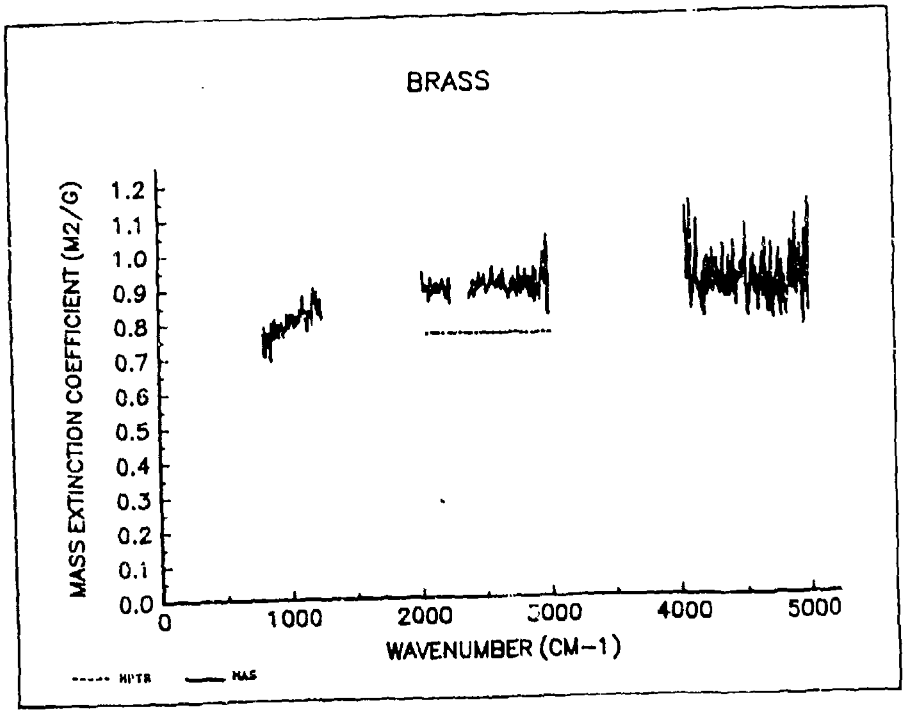

Figure 12. Spectrally resolved mass extinction coefficients for brass.

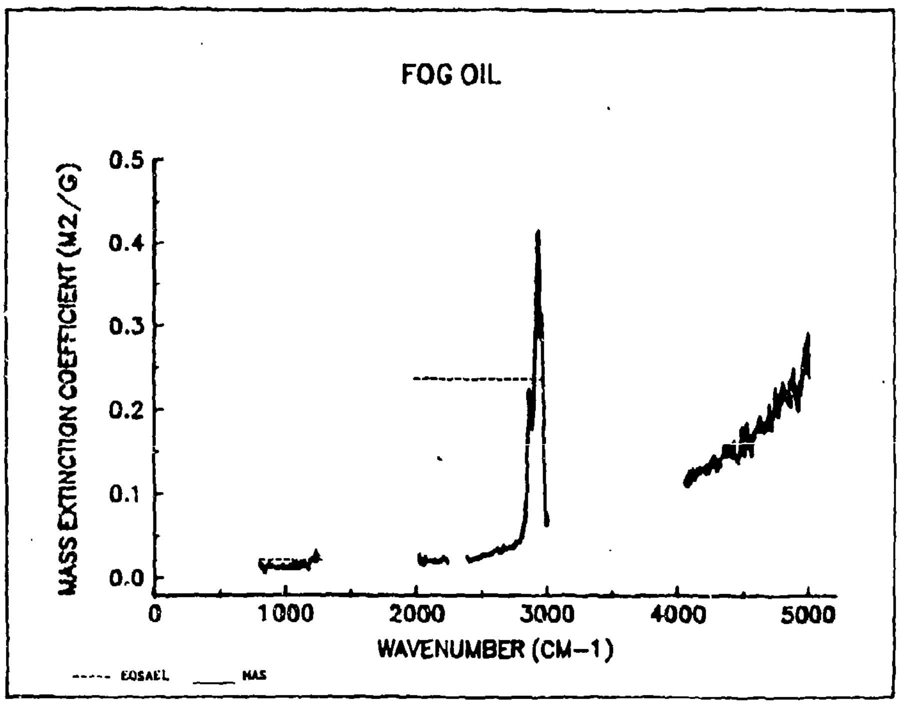

Figure 13. Spectrally resolved mass extinction coefficients for fog oil.

9. Concluding Remarks

All the reduced spectra were provided to the managers of the AAODL database. Each spectrum was provided in two column, comma delimited, ASCII format. The first column is the spatial frequency (wave number) in centimeters^{-1} of each point, and the second column is the transmittance (percent) or radiance (W/cm^2/sr/cm^{-1}).

Among the enhancements employed at Smoke Week XIV were a high-speed parallel spectrometer-to-computer interface and a mechanical chopper at the blackbody source. While these enhancements were not fully optimized, they accounted for a dramatic increase in data acquisition rate and the total number of spectra obtained.

More than 9,000 spectra were collected, and analysis will be a significant task. A 3-D spectral movie that displays transmittance (or radiance) versus spatial frequency as a function of time has been developed, which allows the researcher to view complete trials incorporating hundreds of spectra.

Characterization of obscurant mass extinction coefficients has demonstrated the utility of spectrally resolved measurements.

Recently, a new system has been added to the MAS inventory. The smaller, 4-wheel drive, off-road MAS ROVER provides greater mobility for fenceline and general spectroscopic monitoring. All electronics are powered by 2 banks of 12 V marine batteries. The portable spectrometer with 0.26-m optics monitors in passive or active (double-ended) modes.

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Acronyms

AAODL	Atmospheric Aerosols and Optics Data Library
ARL	Army Research Laboratory
BED	Battlefield Environment Directorate
CL	concentration length
EOSAEL	Electro-Optical Systems Atmospheric Effects Library
FTS	Fourier transform spectrometer
KBr	potassium bromide
MAS	mobile atmospheric spectrometer
MCT	mercury-cadmium telluride
MPTR	multipath transmissometer/radiometer
ZnSe	Zinc Selinide

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